CODE-BASED OPTICAL NETWORKS, METHODS, AND APPARATUS

Field of the Invention

5   The invention pertains to optical communication systems.

Background of the Invention

Optical fibers provide communication bandwidths as large as tens of Terahertz (THz). Such large bandwidths are too large to be fully used

10   by single-channel communication systems that transmit data by amplitude modulation of a narrow-bandwidth optical carrier such as by directly modulating a distributed feedback laser. Factors limiting the bandwidth occupied by simple amplitude-modulated systems include bandwidth limits on available electronic and optical components such as

15   optical modulators and detectors, as well as fiber dispersion.

In order to more fully use the available bandwidth of an optical fiber, multiplexing techniques have been developed that permit several communication channels to use the same optical fiber. The total fiber bandwidth used by these channels can be as large as the sum of the

20   individual channel bandwidths. Conventional methods for multiplexing in optical communication systems include time-division multiplexing (TDM), wavelength-division multiplexing (WDM), and optical-code-division multiple access (OCDMA). These optical multiplexing methods are typically used in long haul, point-to-point communication and in

25   short haul, ring-topology communication systems. Each of these methods has benefits as well as drawbacks associated with it.

A passive optical network (PON) capable of transmitting and receiving data from a large number of users simultaneously reduces cost and increases system reliability. A PON includes passive optical

components that route optically encoded data streams to and from designated users or network nodes. Communication systems based on the Synchronous Optical Network ("SONET") are not PONs since each user or node in a SONET system must have active equipment to detect

5   and demultiplex the data stream to recover data, and then retransmit data to the next user or node.

WDM systems are PONs, but each user of a WDM system is assigned a specific wavelength, so that WDM-based PONs are expensive and are not readily reconfigurable.

10   The use of OCDMA in a PON is advantageous in that data encoded onto a single transmitter can be distributed among many users because data is distinguished by a complex temporal code, and not wavelength as in WDM systems. Furthermore, CDMA coding has the advantage that the number of users is flexible, dependent on system

15   usage. Also, most OCDMA implementations inherently offer hardware encryption by making channel decoding difficult without knowledge of the OCDMA encoding scheme. However, flexible tree-architecture PONs based on OCDMA typically require expensive equipment that must be located at each network node or an end-user location. Therefore,

20   improved systems, methods, and architectures are needed for practical PON OCDMA systems.

Brief Description of the Drawings

FIG. 1 is a schematic block diagram of a communication system

25   that includes a passive optical network (PON).

FIG. 2 is a schematic block diagram of the central station of FIG. 1.

FIG. 3 is a schematic block diagram of a representative level-A multiplexing (mux) station.

FIG. 4 is a schematic diagram of a level-A address encoder.

FIG. 5 is a schematic diagram of a level-A address decoder.

FIG. 6 is a schematic diagram of a representative level-B mux station.

5   FIG. 7 is a schematic diagram of a level-B address decoder.

FIG. 8 is a schematic diagram of a level-B address encoder.

FIG. 9 is a schematic diagram of a representative user station of the communication system of FIG. 1.

FIG. 10 is a schematic diagram of a data-transmission system
10   using 3-chip supercodes and 3-chip subcodes.

Detailed Description

FIG. 1 illustrates an optical communication system 100 comprising a central station 103 that distributes optically transmitted
15   data (telephony, internet, video, etc.) to a number of geographically separated users 117_{11}, . . ., 117_{nm} that communicate with the central station 103 via a passive optical network 151. In addition, the central station 103 collects data from the user stations 117_{11}, . . ., 117_{nm} for remote transmission via an optical communication link 121. For
20   convenience in describing the communication system 100 and other communication systems and apparatus, a "downstream direction" is defined as a data-propagation direction from a central station to a user. An "upstream direction" is a data-propagation direction from a user to a central station.

25   In the communication system 100, multiple data streams are multiplexed and demultiplexed by using optical-code-division multiple access (OCDMA). As shown in FIG. 1, the communication system 100 has a tree architecture with a level-A mux station 111 and level-B mux stations 113_1, . . ., 113_n. While FIG. 1 shows the level-A mux station

111 as a single branch from the central station 103, the central station 103 can communicate with multiple level-A mux stations.

FIG. 2 is a schematic diagram of the central station 103. The central station 103 comprises an input data module 201 that receives

5   data transmitted to or produced at the central station 103. As shown in FIG. 1, the central station 103 receives data from an external data link 121 or from the level-A mux station 111. Returning to FIG. 2, the input-data module 201 delivers an electrical data signal to an optical transmitter 203 that includes an optical emitter such as a distributed

10   feedback laser. The laser is modulated in response to the electrical data signal so as to produce an optical data signal. Alternatively, an emitter can be provided that emits a continuous optical signal or a periodic series of optical pulses that are modulated with an electro-optic, acousto-optic, electro-absorptive, or other modulator. The modulation

15   can be amplitude-modulation or phase-modulation or a combination thereof.

A central station address encoder 205 receives the optical data signal from the optical transmitter 203 and encodes the modulated optical signal with an optical code such as a composite code serving as

20   an address for a selected user. In an alternative embodiment, the central station address encoder 205 can include encoders for every user (a total of *nxm* encoders), or a smaller number of programmable encoders depending on system requirements, e.g., the aggregate downstream bandwidth and the number of users to be simultaneously

25   addressed.

Composite codes are described in a U.S. Patent Application entitled CODES, METHODS, AND APPARATUS FOR OPTICAL ENCODING AND DECODING, co-filed with the present application and incorporated herein by reference. Representative encoders and decoders

using fiber Bragg gratings are described in U.S. Patent App. No.

09/354,851, TIME-WAVELENGTH MULTIPLE ACCESS

COMMUNICATION SYSTEM that is incorporated herein by reference.

The composite codes are made of one or more code sets, each

5   code set corresponding to the number of mux levels. In the two-node

(two mux levels) network of FIG. 1, the central station address encoder

205 applies composite codes having two levels A, B corresponding to

level-A codes and level-B codes. If a third group of nodes were provided

(i.e., if a level-C mux station were placed between the level-B mux

10   stations 113_1, . . ., 113_n and user stations 117_{11}, . . , 117_{nm} to provide

a third level of coding), then the central station address encoder 205

could apply the level-C codes. In such a case, the composite codes

would include A-level, B-level, and C-level codes. Composite-code

encoders can be configured in a variety of ways as described in the

15   references cited above.

Returning further to FIG. 2, an output module 207 of the central

station 103 delivers combined optically coded (composite-coded) data

signals from the encoders of the central station address encoder 205,

and delivers a coded optical signal to the level-A mux station 111. The

20   coded signal delivered to the level-A mux station 111 is encoded with

level-A and level-B codes that designate a user station to which data is

to be delivered.

The central station 103 further comprises an input module 209

that receives optical signals from the level-A mux station 111 and

25   delivers optical signals to a central station address decoder 211 that

decodes the level A and level B codes with which the optical signals are

encoded. After the optical signals are thus decoded, an optical receiver

213 produces an uncoded electrical signal corresponding to the decoded

optical signal, and an optical transmitter ("output data module") 215 transmits a corresponding optical signal on the communication link 121.

FIG. 3 is a schematic diagram of the level-A mux station 111. An input module ("input means") 301 of the level-A mux station 111

5   accepts optical, composite-coded data signals from the central station 103. The input module 301 directs the optical data signals to a level-A address decoder/router 303. Output modules ("output means") 305_1, . . ., 305_n receive optical data signals from the level-A address decoder/router 303, split the received optical data signal into n optical

10   data signals, and transmit these signals to respective level-B mux stations 113_1, . . ., 113_n.

The level-A mux station 111 also includes input modules ("input means") 307_1, . . ., 307_n that receive optical data signals from respective level-B mux stations 113_1, . . ., 113_n. A level-A address

15   encoder 309 applies a level-A code to the received optical signals and directs the encoded optical signals to an output module ("output means") 311 for delivery to the central station 103.

FIG. 4 is a schematic diagram of the level-A address decoder/router 303. A beam splitter ("beam splitting means") 403 or a

20   fiber directional coupler receives optical signals from the input module 303 and directs portions of the optical signals to optical circulators 405_1, . . ., 405_n that, in turn, direct respective portions of the optical signals to corresponding complex fiber Bragg gratings 401_i, . . ., 401_n that decode level-B codes. Decoded optical signals are delivered to

25   corresponding outputs 409_1, . . ., 409_n that deliver a respective decoded optical signal to a corresponding level-B mux station. The optical signals for the respective level-B mux stations 113_1, . . ., 113_n can be broadcast, and data not intended for delivery to a particular level-B mux station (and ultimately to a selected user station) is not properly

decoded at the decoder/router 303. For data decoded with an
unmatched decoder, the optical signal is typically a noise-like, low-
power signal.

FIG. 5 is a schematic diagram of the level-A address encoder 309.

5   Level-B coded optical signals are received at corresponding inputs
$509_1, \ldots, 509_n$ and delivered to respective optical circulators
$511_1, \ldots, 511_n$ and respective fiber Bragg gratings $513_1, \ldots, 513_n$.
After encoding with level-A codes by the fiber Bragg gratings $513_1, \ldots,$
513_n, encoded optical signals are combined by a beam combiner ("beam

10   combining means") 515 for delivery to the output module 311 and the
central station 103.

FIG. 6 is a schematic diagram of a representative level-B mux
station 113_i. The level-B mux station 113_i includes an input module
("input means") 601_i that accepts an optically coded data signal from

15   the level-A mux station 111. A level-B address decoder/router 603_i
receives the optical data signal and splits the optical data signal into m
corresponding optical data signals $604_{i1}, \ldots, 604_{im}$, corresponding to
the m user stations $117_{i1}, \ldots, 117_{im}$. Output modules $607_{i1}, \ldots, 607_{im}$
transmit the split optical data signals $604_{i1}, \ldots, 604_{im}$.

20   FIG. 7 is a schematic diagram of the representative level-B
address decoder/router 603_i. A beam splitter ("beam splitting means")
703_i or a fiber directional coupler receives an optical signal from the
level-A mux station 111 and directs respective portions of the optical
signal to optical circulators $705_{i1}, \ldots, 705_{im}$ that, in turn, direct the

25   respective portions to corresponding fiber Bragg gratings
$701_{i1}, \ldots, 701_{im}$ that decode level-B codes. The optical signal from the
level-A mux station 111 can be broadcast to the respective level-B mux
station because data not intended for delivery to a particular level-B mux
station (and ultimately to a selected user station) is not properly

decoded in the decoder/router 603_i. For data decoded with an unmatched decoder, the optical signal is typically a noise-like, low-power signal and data is not readily recovered from such signals.

FIG. 8 is a schematic diagram of the level-B encoder 611_i. Optical

5   signals are received from user stations 117_{i1}, . . ., 117_{im} at respective inputs 801_{i1}, . . ., 801_{im} and delivered to respective optical circulators 803_{i1}, . . ., 803_{im} and fiber Bragg gratings 805_{i1}, . . ., 805_{im} that encode level-B codes. Encoded optical signals propagate along fiber lengths 807_{i1}, . . ., 807_{im} to a beam combiner ("beam combining

10   means") 811_i, and the combined optical signal is delivered to the level-A mux station 111.

The user stations 117_{il}, . . ., 117_{nm} include respective interface modules, such as a representative interface module 901_{ij} shown in FIG. 9. The interface module 901_{ij} comprises an output module ("output

15   means") 903_{ij} and an input module ("input means") 905_{ij} that send data to and receive data from a corresponding level-B mux station 113_i. The input module 905_{ij} receives a decoded optical signal from the corresponding decoder of the level-B mux station 113_i. An optical receiver 907_{ij} converts the decoded optical signal into a corresponding

20   electrical signal. If the decoded optical signal originated at the central station 103 and was encoded with the level-A and level-B codes associated with the selected user station 117_{ij}, then the electrical signal includes a series of data pulses. If the level-A and level-B codes applied at the central station 103 have not been properly decoded, then the

25   electrical signal is a noise-like signal that can include some electrical pulses similar to data pulses but having smaller magnitudes. The optical receiver 907_{ij} can include circuitry for removing or attenuating these smaller pulses and the noise-like background by thresholding and/or digitization, producing an enhanced electrical data output signal. The

data output module delivers the electrical data output signal to a module output 911_{ij}.

For communication in an upstream direction, i.e., from a user station 117_{ij} towards the central station 103, an input module 913ij

5   receives data from a user input 915_{ij}. The received data modulates an optical transmitter ("modulated optical source") 917_{ij} and the output module 903_{ij} transmits an uncoded optical signal to a level-B mux. The optical transmitter 917_{ij} can include a laser diode that is directly modulated by the received data, or that is modulated by an electro-

10   optic, acousto-optic, electro-absorptive, or other modulator. Corresponding level-A and level-B mux stations apply level-A and level-B codes to the uncoded optical signal, and the coded signal arrives at the central station 103 where it can be decoded for transmission by stripping the level-A and level-B codes that indicate the data source.

15   Returning to FIG. 1, the PON 151 includes coders (encoders and decoders, not shown) that apply and strip codes from optical data signals. These coders require no power, nor is an optical-to-electrical conversion needed in the PON 151. In some cases, partially encoded and decoded optical signals are broadcast, but data generally cannot be

20   recovered from these broadcast optical signals unless decoded and encoded with matching codes. Hence, the PON 151 is "secure."

The embodiments described herein comprise encoders and decoders that include optical circulators and reflective complex fiber Bragg gratings. Other coding methods and apparatus can be used.

25   Such methods and apparatus also apply selected linear spectral transforms to optical signals. Furthermore, other methods and apparatus, such as beam splitters or fiber couplers, can be used to separate counterpropagating optical data signals instead of optical circulators. Representative optical encoders and decoders include

passive diffractive devices such as Bragg gratings and fiber Bragg gratings as described in, for example, U.S. Patent No. 5,812,318; U.S. Patent Application Nos. 09/115,331, SEGMENTED TASM GRATINGS, 09/120,959, SEGMENTED COMPLEX FIBER GRATING, and

5   09/354,851, TIME WAVELENGTH MULTIPLE ACCESS COMMUNICATION SYSTEM. These documents are incorporated herein by reference.

The communication system 100 of FIG. 1 can include optical amplifiers if necessary, based on system-design parameters such as

10   fiber loss, desired signal-to-noise level, intended number of users, acceptable bit-error rate, and others. Dispersion compensation can be provided in the PON 151 and a wavelength-division-multiplexed (WDM) layer can be provided in addition to the code layer. In addition, embodiments are discussed with reference to optical signals that are

15   electromagnetic fields of wavelength from about 300 nm to 0.1 mm. However, embodiments using longer or shorter wavelength electromagnetic fields are possible and electrical voltages carried by conductors such as wires can be used as well.

For convenience in describing embodiments, decoders were

20   referred to as "stripping" a code from a signal. Decoding generally permits data recovery by a detector, and decoding need not restore a signal exactly to its pre-encoded form. In addition, a signal from which a code has been stripped can be referred to as a "decoded" signal. Finally, for clarity, encoders and decoders are referred to in the above

25   description, but can be more generally referred to as "coders."

For convenience, composite codes that include two code levels and suitable for use in a passive optical network and in address encoders/decoders are described with reference to FIG. 10. FIG. 10 is a schematic of a data transmission system 1001 that produces a data

signal 1003 from a data source 1005. As shown in FIG. 10, the data

signal 1003 is represented as a binary, on-off modulation of an

electromagnetic carrier such as an optical carrier. The on-off modulation

is selected for convenience only, and other modulations can include

5   phase, amplitude, intensity, and frequency modulation. In addition, non-

binary modulation having more than two modulation levels can be used.

A supercode encoder 1007 receives the data signal 1003 and

applies a predetermined code R_i selected from a code set R to the data

signal 1003. For purposes of illustration, a code $R_i = \{1, -1, 1\}$ is

10   selected and applied to a representative bit 1009 of the data signal

1003. As specified by the code R, the encoder 1007 receives the bit

1009 and transforms the bit into a "supercoded" bit packet 1011. The

supercoded bit packet 1011 includes super-coded bits ("superbits")

1013-1015 that are relatively delayed by a delay time T_{RC}, wherein T_{RC}

15   is a supercode chip duration. In addition, the phase of the superbit

1014 is inverted, while the phases of the superbits 1013, 1015 are

unchanged. The encoder 1007 applies the code R_i to the entire data

signal 1003 to produce a supercoded data signal that is a sum of

superbits corresponding to all respective bits of the data signal 1003.

20   A subcode encoder 1017 receives the supercoded data signal and

applies a code S_i selected from a code set S. For purposes of

illustration, a code $S_i = \{-1, 1, -1\}$ is selected. The code S_i is applied to

the supercoded bit packet 1011 to produce a combined subcoded and

supercoded ("composite-coded") bit packet 1021 that includes

25   subcoded bits 1023, 1025, 1027, corresponding to respective superbits

1013, 1014, 1015. The encoder 1017 encodes each of the supercoded

bits 1013-1015 by relatively delaying portions by a delay time T_{SC}

wherein T_{SC} is a subcode chip duration, and changing the phase of the

supercoded bits 1013, 1015, to produce the corresponding subcoded

bits 1023, 1025, 1027. The encoder 1017 applies the code S_i to the supercoded data signal, producing a composite-coded data signal.

The encoders 1007, 1017 apply codes from respective sets R, S to the data signal 1003. If the sets R, S contain N_R and N_S codes,

5   respectively, then N_R x N_S different encodings are available. For example, if sets R, S each include 5 codes, then 25 encodings are possible. Thus, the number of available encodings increases as the product of N_R and N_S increases so that large numbers of encodings are possible even with small code sets. In addition, the sets R, S can be

10   subsets of a large code set and can include different or identical codes. In this way, a set of N codes can be used to produce N^2 different encodings.

FIG. 10 illustrates encoding, with two sets of codes (sets R, S), but additional code sets can be used to further increase the number of

15   available encodings. Subcode bits 1013-1015 can be further encoded with a code set Q having N_Q codes, so that the number of available encodings is N_R x N_S x N_Q. Codes obtained by combining two or more code sets such as the code sets R, S are referred to herein as "composite codes." Composite codes using code sets R, S and code

20   sets R, S, Q are suitable for networks having two and three levels of address encoding/decoding, respectively.

The codes R_i, S_i used above are selected as representative examples. More generally, codes include two or more "chips" that specify modulations to be applied to a signal. The chip modulations are

25   applied to a signal at relative times differing by a chip duration T_C. Thus, a code and a chip duration specify an encoding of a data signal. A supercode is further specified by an interchip duration. A code R, having a total duration T_R, a number of chips N_R, and a chip duration T_{RC}, and a code S, having a total duration T_S, a number of chips N_S, and chip

duration or interchip delay T_{SC}, are effectively orthogonal as decoded if $T_R \le T_{SC}$. A composite code can be produced from the code R (a subcode), and from the code S (a supercode). The composite code has a given duration equal to the duration of the supercode and has a

5   number of chips equal to the product of the number of chips of the subcode and the supercode. The chip duration is equal to the subcode chip duration. In the composite code, the subcode is repeated a number of times equal to the number of chips in the supercode.

Code sets and chip durations of supercodes and subcodes (and

10   sub-subcodes) are preferably selected so that a data signal encoded with a particular composite code is decoded only with a matching decoding composite code. Decoding with an unmatched composite code produces only a noise-like background or low amplitude "sidelobes" or "crosstalk."

15   Given temporal orthogonality between a supercode and the subcode (i.e., low-amplitude cross-correlation and noise-like background), composite code sets of sufficient orthogonality can be generated from a code set with a small number of chips if the codes of the code set are sufficiently orthogonal. A code in a composite code set

20   is generated by using a selected code of the code set as a supercode and another selected code of the code set as a subcode. A composite code set comprises all combinations of supercodes and subcodes. For example, if a code set has M codes each containing N_m chips, then the composite code set contains M x M codes each having N_mxN_m chips.

25   Having illustrated and demonstrated the principles of the invention, it should be apparent to those skilled in the art that the embodiments described can be modified in arrangement and detail without departing from such principles. We claim as the invention all that comes within the scope of these claims.